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Prioritization of knowledge needs for sustainable aquaculture: a national and global perspective

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Abstract

Aquaculture is currently the fastest expanding global animal food production sector and is a key future contributor to food security. An increase in food security will

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be dependent upon the development and improvement of sustainable practices. A prioritization exercise was undertaken, focusing on the future knowledge needs to underpin UK sustainable aquaculture (both domestic and imported products) using a 'task force' group of 36 'practitioners' and 12 'research scientists' who have an active interest in sustainable aquaculture. A long list of 264 knowledge needs related to sustainable aquaculture was developed in conjunction with the task force. The long list was further refined through a three stage process of voting and scoring, including discussions of each knowledge need. The top 25 knowledge needs are presented, as scored separately by 'practitioners' or 'research scientists'. There was similar agreement in priorities identified by these two groups. The priority knowledge needs will provide guidance to structure ongoing work to make science accessible to practitioners and help to prioritize future science policy needs and funding. The process of knowledge exchange, and the mechanisms by which this can be achieved, effectively emerged as the top priority for sustainable aquaculture. Viable alternatives to wild fish-based aquaculture feeds, resource constraints that will potentially limit expansion of aquaculture, sustainable offshore aquaculture and the treatment of sea lice also emerged as strong priorities. Although the exercise was focused on UK needs for sustainable aquaculture, many of the emergent issues are considered to have global application.

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Introduction

In 2010, global aquaculture production attained 59.9 Mt year^{-1} excluding plant and non-food products (FAO 2012). Aquaculture production is predicted to rise to 85 Mt year^{-1} by 2030 (FAO 2007). Having expanded almost 12-fold in the last three decades (at an average annual rate of 8.8%), aquaculture production contributed to almost half (45%) of world food fish production in 2012 (FAO 2012). The first sale value of these products was valued at US$119.4 billion, of which marine-based aquaculture contributed 29.2% (FAO 2012). The rapid development of the aquaculture sector can be attributed to a combination of factors: market demand (and competition), the emergence and rapid introduction of new technologies, and increasing commercialization within the aquaculture industry (Tacon 1997; Bostock *et al.* 2010). In the case of several species, the aquaculture industry has been able to far exceed the production from the capture fishing industry and provides a much more consistent, predictable and steady supply of product to the market place (Eagle *et al.* 2004; FAO 2006, 2009, 2012). For example, <1% of annual Atlantic salmon (*Salmo salar*, Salmonidae) production originates from wild capture fisheries while 55% of global shrimp and prawn production is farmed (FAO 2012). The human population is projected to reach 9 billion by 2050 necessitating a considerable increase in food production (World Population Prospects 2012). Farmed aquatic products have an important future role to play in food production as they have the potential to meet the increasing demand for nutritious food as well as supporting local and national economies (Naylor *et al.* 2000; FAO 2006).

Globally, the aquaculture sector is extremely diverse (and much more diverse than land-based sources of animal protein), ranging from small-scale artisanal ponds in developing countries to industrialized multinational companies with annual turnovers exceeding US$1 billion (Bostock *et al.* 2010). Regional disparity in the growth of the industry is evident, with a significant majority of production now taking place in China and South East Asia (FAO 2006, 2009, 2012). Despite limited expansion in recent years, the UK contributes *c.* 8% to total European aquaculture production (marine and freshwater) and is the fourth highest European producer behind Norway, Spain and France (FAO 2012). Given the regional disparity in production, the market for aquaculture products is highly globalized and the UK imported £2.6 billion worth of fish and shellfish products in 2012 from global suppliers (Seafish 2013). Thus as retailers need to draw on global supplies of aquaculture products, any consideration of issues that impact upon the sustainability of such production needs to include these issues at all levels (local, national, regional, and international; Frankic and Hershner 2003).

The importance of sustainable aquaculture in food security was identified by the FAO (2011). The European Union is currently developing the 'European Marine and Fisheries Fund' which could fund innovative aquaculture projects from 2015 (European Commission 2011). Despite the recognition of the importance of aquaculture for food security, the sustainability of intensive marine aquaculture, along with its associated ecological impacts, has been identified as key limiting factor (Goldburg and Triplett 1997; Naylor *et al.* 2000, 2009; Diana 2009). Accordingly, policymakers need to regulate the sector to balance the dual needs of sustaining natural resources and promoting aquaculture development to ensure maximum benefits to society in the long term (Frankic and Hershner 2003; Subassinghe *et al.* 2009; FAO 2012).

The process of knowledge exchange is often overlooked within the research community. Increasingly this is receiving more attention from funding agencies, not least because of the need to account for the impact of the expenditure of public resources. The identification of knowledge needs that are of relevance to policymakers and practitioners and the prioritization of these needs is itself a research exercise, for which a systematic methodology has been developed (Sutherland *et al.* 2006, 2011). Terrestrial examples of its application include the identification and prioritization of questions of policy relevance in the fields of ecology (Sutherland *et al.* 2006), agriculture (Pretty *et al.* 2010), and knowledge needs for evidence-based conservation of wild insect pollinators (Dicks *et al.* 2012) for enhanced sustainable agriculture (Dicks *et al.* 2013), UK food security (Ingram *et al.* 2013) and even poverty alleviation (Sutherland *et al.* 2013). The strength of this methodology lies in the implementation of a collaborative, cross-sectoral approach based on 'experiential, theoretical and empirical knowledge' (Nutley *et al.* 2007; Dicks *et al.* 2012).

The process and its outputs have had a high impact, specifically in shaping national science policies. For example, in the UK Government's Marine Science Strategy (DEFRA 2010), research questions across each section were acknowledged as being informed by the 'UK 100 ecology questions exercise' (Sutherland *et al.* 2006). Moreover, the questions identified by Pretty *et al.* (2010) informed the initial priorities of the UK's Global Food Security Research Program. Thus, while these initiatives are necessarily country specific, they present a model approach with global application. The latter is particularly relevant to aquaculture as the consideration of issues of importance to the UK is necessarily global as the majority of aquaculture products are imported. The present paper sought to identify and prioritize knowledge gaps that, if addressed, would lead to significant advances in sustainable aquaculture production either nationally or globally, or that would improve best practice within the industry

(Frankic and Hershner 2003; Subassinghe *et al.* 2009).

Methods

To identify and prioritize knowledge needs pertinent to facilitate the expansion of sustainable aquaculture, a two-stage process was implemented. This was based on the methodologies of Sutherland *et al.* (2011) and Dicks *et al.* (2012). In stage 1, knowledge needs were collaboratively identified by a wide range of stakeholders (Appendix S1). In stage 2, the resultant list of needs that had been generated was prioritized during two voting sessions followed by a final scoring session. The generation of knowledge needs and initial voting session were conducted remotely (online using Excel). The final voting and scoring sessions were conducted at a 2-day workshop held in Fishmongers' Hall, London, on the 25 and 26 February 2013.

Who was involved?

In total, 48 stakeholders participated in one or more stages of the process and are included as authors. Participants involved in the process were categorized as either 'research scientists' (n = 12) or 'practitioners' (n = 36). The term 'research scientist' refers to participants involved in active research within the field of marine-based aquaculture. Ten expert scientists with a range of specialisms (ranging across molluscs, crustaceans and finfish) were selected to help the discussion of knowledge needs throughout the process, these individuals were termed 'the expert steering group'. The term 'practitioner' refers to all other participants with an interest in sustainable aquaculture and food security across a wide range of levels (36 participants). The practitioners included representatives from three large UK supermarkets, six seafood trade organizations, seven fish farms or farming associations, six environmental non-governmental organizations (eNGOs) and four government departments or agencies with responsibilities that relate to UK aquaculture.

Identification of knowledge needs

The following process is summarized in a flow diagram (Fig. 1). Participants were asked to identify areas where scientific knowledge is most needed (and is currently lacking) to facilitate the expansion of sustainable aquaculture, thus moving towards more sustainable food production and improved UK food security. To clarify the scope, participants were informed that knowledge needs could be based on both the UK supply chain and the external supply chain from countries that supply aquaculture products to UK food markets. Each participant was requested to submit up to 10 specific knowledge needs that could be answerable through scientific research within a 3–5 year period. As a guide, participants were provided with 10 example knowledge needs developed through a comparable exercise that had focused improving the environmental sustainability of agriculture for the UK food system (Dicks *et al.* 2013).

Knowledge needs with a similar theme were grouped by the first four authors (Table 1; Appendix S2). Each knowledge need featured on the list once only. Categories identified *post hoc* were the following: (i) feed, (ii) disease, (iii) husbandry methods and technology, (iv) aquaculture and the environment (including climate change), (v) marine planning, management and policy, (vi) aquaculture supply, demand, trade and marketing. The

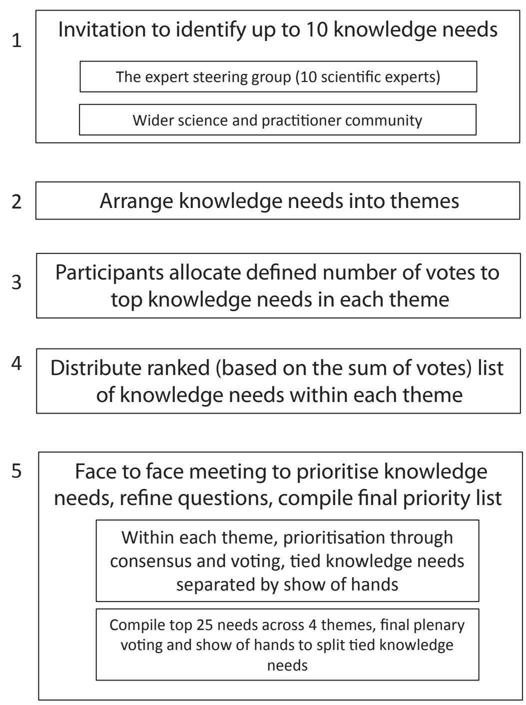

Figure 1 Schematic flow diagram to illustrate the different stages in the prioritization process as described in the methodology.

Table 1 Content of six sustainable aquaculture knowledge-need categories and number of proposed knowledge needs within each category.

Category	Key	Description of proposed knowledge needs	Number
Feed	F	Economical and sustainable alternatives to fish oil and fish meal, GM feed sources, nutritional requirements of fish and shellfish	36
Husbandry methods and technology	H	Integrated multitrophic aquaculture (IMTA), development of technology for offshore aquaculture, systems for treatment of aquaculture effluents, breeding programmes	45
Aquaculture and the environment (including climate change)	E	Reducing overall environmental impact of aquaculture, impacts on local biodiversity, risks from escapees to biodiversity, impact of climate change, water quality	59
Marine planning, management and policy	P	Co-location of aquaculture and renewable energy, potential areas in the UK for expansion of aquaculture, area-based management schemes, planning and development of integrated multitrophic aquaculture systems	37
Aquaculture supply, demand, trade and marketing	S	Sustainability of aquaculture compared to other forms of food production, aquaculture production in developing countries, consumer attitudes to GM animals, promotion of new species for UK cultivation, ecosystem services from aquaculture	47
Disease	D	Detection of viral contaminants of shellfish, amoebic gill disease in Salmon, treatments for sea lice in salmon	37

number of knowledge needs within each category ranged from 36 to 59 (Appendix S2).

Prioritization of knowledge needs

In the first voting stage, participants voted remotely on the long list of knowledge needs. The original wording of the individual knowledge needs was retained to avoid misinterpretation of the author's intention and to allow transparency in the process. Participants were asked to select 20% of the items listed within each category that represented the most pressing knowledge needs to enable the expansion of sustainable aquaculture. When a group of similar knowledge needs were identified, participants were asked to select the one that best addressed the overall knowledge need. The opportunity was given to make anonymous comments and/or suggest alternative wording for a specific knowledge need. The knowledge needs in each category were ranked according to the number of votes that each received. Both the anonymous comments and the number of votes were visible to participants during the subsequent workshop.

At the workshop, knowledge needs were discussed during 90-min sessions dedicated to each of the six categories listed above. Two sessions ran in parallel; therefore, each participant was involved in three discussion sessions. Each session had approximately equal numbers of participants and captured a wide range of interests and expertise. Social psychologists have demonstrated that expert judgement is best attained in this manner (Hussler *et al.* 2011; Yaniv 2011). As the discussion sessions were designed to be practitioner-led, groups contained a maximum of six research scientists to prevent them dominating the discussion. Group numbers were small enough to encourage discussion, yet large enough to enable a consensus position to be reached. Research scientists were asked to provide insight into completed and ongoing research surrounding each knowledge need. Practitioners were asked to identify knowledge needs that, if met, would lead to their organizations changing policy or practice, with the objective of enhancing the sustainability of their production or supplies. Each session had a neutral chairperson to facilitate the discussion process without influencing the decisions.

Knowledge needs with more votes were allocated more discussion time. Nevertheless, sufficient opportunity was afforded to discuss knowledge needs with few or no votes as previous experience demonstrates that some of these questions may be promoted after discussion (Dicks *et al.* 2013). At this stage, any re-wording or amalgamation of knowledge needs was established through group consensus. Through discussion, knowledge needs were eliminated to create a short list within each category. A maximum of 20% of the original list was retained. Voting by show of hands was used to prioritize the short list of knowledge needs from each session. An additional round of voting was implemented where the votes allocated to two or more knowledge needs were equal. A list of 42 knowledge needs, drawn from across all six category sessions, was generated (Appendix S3). This list was ordered according to rank from within each session. Knowledge needs from different categories were evenly dispersed throughout the list to reduce the effects of voter fatigue and bias introduced by ordering effects.

A plenary session was dedicated to the final voting stage and involved all workshop participants. Each of the 42 knowledge needs was briefly clarified (for the benefit of those who had not been in the relevant sessions). By unanimous decision, the participants added a supplementary knowledge need to the list at this stage: 'Mechanisms for knowledge exchange'. This followed a comment that it was obvious from interactions between scientists and practitioners during the earlier voting sessions that knowledge exchange itself was missing from the list of knowledge needs. Individual participants privately scored each knowledge need on a scale between 0 and 10, with 10 being of highest importance. They were requested to score across the full range of values. Workshop facilitators and observers did not vote or score the questions at any stage.

Analysis of results

Based on the 42 knowledge needs that emerged through the workshop, a final list of the top 25 priority knowledge needs was identified according to the summed practitioner scores (Table 2). Knowledge needs were ranked initially by the median practitioner score. When practitioner scores were equal, knowledge needs were ordered according to the rank from both practitioners and research scientist scores combined and thereafter ranked according to lowest inter-quartile range (least variability).

Using SPSS version 20 (IBM, Armonk, NY, USA), a Friedman test was used to identify whether any of the 42 knowledge needs were scored significantly differently from others. In order to understand to what extent practitioners and scientists agreed or disagreed in their prioritization of the knowledge needs a Spearman's rank correlation coefficient was used to assess the correlation between practitioner and research scientist median scores for each knowledge need. We investigated differences in the ranking accorded to each of the top 25 knowledge needs. To do this, the score allocated by the scientists was subtracted from the score given by the practitioners. The value of the difference in score between the two groups was plotted against the rank of the associated knowledge need. A regression analysis of this relationship was undertaken using Minitab v16 (Minitab Ltd., Coventry, UK).

Multivariate analysis

Data were analysed using PRIMER 6.1 (Plymouth Routines in Multivariate Ecological Research, Plymouth Marine Laboratory, Plymouth, UK) to further determine any significant differences in the scoring patterns of practitioners and research scientists (Clarke 1993; Clarke and Gorley 2006). Score data were arranged into a resemblance matrix and fourth root transformed. This ensured that the similarity coefficient used (Bray-Curtis) was invariant to scale change (Bray and Curtis 1957; Field *et al.* 1982).

A non-metric Multidimensional Scaling ordination plot was generated to show the similarities or differences that occurred in the scores given by the practitioners and scientists (Bray and Curtis 1957; Field *et al.* 1982; Clarke and Gorley 2006). This analysis would indicate whether the population of questions chosen by either practitioners or scientists differed and whether the distribution of scores among the knowledge needs was different for these two groups. Significant differences between practitioner and research scientist scores were detected using nonparametric one-way analysis of similarities (ANOSIM). This method of analysis was applied across the full range of potential knowledge needs (n = 42) and within each of the six categories.

An analysis of the contribution of similarity (SIMPER) of scores for each knowledge need submitted by practitioners and scientists was carried out. Contributions to the first 50% cumulative dissimilarity between practitioners and scientists were initially identified from the SIMPER output. Knowledge needs that contributed significantly to the dissimilarity between practitioner and research scientist scores were identified using a ratio value of $\geq$1.5 (Diss/SD). This is the ratio of the average contribu-

Table 2 Top 25 priority knowledge needs to facilitate the expansion of sustainable aquaculture. Ranked by median practitioner score (Pmed; 1 = low priority, 10 = high priority). When practitioner scores were equal, knowledge needs were ranked according to overall medians [both practitioner and scientist median scores (Omed)] then according to lowest interquartile range (IR). All knowledge needs with a median of 7 or more by either practitioners or scientists are included. Research scientist median scores are given separately (Smed). Category codes are explained in Table 1, except KE (Knowledge Exchange). This knowledge-need category is not included in Table 1 as it was proposed during the final voting stage of the workshop. Scale indicates where a knowledge need relates specifically to the UK or has global application.

No.	Knowledge need	Category	Pmed	Smed	Omed (IR)	Scale
1	Mechanisms for knowledge exchange, to communicate and interpret current scientific knowledge to the practitioner audience	KE	9	7	9 (2.3)	Global
2	What are the alternative sources of protein and oil for use in aquaculture feeds that are sustainable, technically and economically feasible and nutritionally suitable for the cultured livestock, and that also meet consumer nutritional needs and acceptability?	F	9	7	9 (4)	Global
3	How does resource availability (fishmeal, water, space and others) constrain the potential of aquaculture to meet the increasing demand for seafood?	S	9	6	8 (3)	Global
4	Development of technology to enable safe, sustainable and economically feasible offshore aquaculture	H	8	6.5	8 (3)	Global
5	What technologies can be developed to increase the range and flexibility of available treatments and integrated management techniques to control sea lice infections on marine-farmed fish?	D	8	8	8 (3.8)	Global
6	Identify and develop solutions for the constraints (biological, economic, legislative and environmental) hampering expansion of the UK shellfish industry	S	8	6.5	7 (2)	UK
7	What are the environmental and socioeconomic effects that might occur with expansion of aquaculture in the offshore environment?	E	7	7.5	7 (2)	Global
8	How can different aquaculture technologies enhance ecosystem services and increase the carrying capacity of fisheries?	P	7	6	7 (2)	Global
9	What is the feasibility of co-locating aquaculture and renewable energy installations in UK waters and what are the implications of doing so?	P	7	8	7 (3)	UK
10	What are the impediments and opportunities in developing integrated multitrophic aquaculture?	P	7	6	7 (3)	Global
11	How can depuration be enhanced through acceptable novel methods to reduce or eliminate viral contaminants from shellfish?	D	7	6	7 (3)	Global
12	What new feed additives and micro-nutrients can be developed or used to improve or complement uptake and utilization of bulk nutrients in aquaculture feeds?	F	7	7	7 (3.5)	Global
13	How can we rapidly distinguish between disease-causing and non-pathogenic forms of norovirus?	D	7	6	7 (4)	Global
14	How can we simplify and speed-up the consenting regime and regulatory process in the UK?	P	7	8.5	7 (4)	UK
15	How do imported and locally produced aquaculture products in the UK compare, with regard to food security in producing countries and at home?	S	7	4	6 (4)	UK/ Global
16	Globally, which elements of best practice in pest management and biosecurity from advanced aquaculture systems can be applied in emerging aquaculture systems?	H	7	4	5 (4)	Global
17	What socioeconomic and coastal infrastructure benefits and synergies can be identified and encouraged, to enhance local cooperation and coexistence of aquaculture and capture fishery interests?	P	6.5	7	7 (4)	Global
18	How can we ensure consumer confidence in the integrity of the aquaculture supply chain by mapping risks, identifying mitigation actions, and what is the role of certification in this process?	S	6.5	7	7 (5)	Global
19	What are the environmental drivers that cause harmful algal blooms and can they be predicted?	E	6	5	6 (2)	Global

Table 2 Continued.

No.	Knowledge need	Category	Pmed	Smed	Omed (IR)	Scale
20	What environmental impacts might result from an expansion of aquaculture in the freshwater environment and what precautions can be taken to mitigate for these impacts?	E	6	5	6 (3)	Global
21	What are the nature and extent of ecosystem services provided by shellfish cultivation?	E	6	5.5	6 (3)	Global
22	Undertake a systematic review of the impact of aquaculture on wild Atlantic salmon	E	6	8	6 (4)	Global
23	How can amoebic gill disease of salmonids be avoided, prevented or effectively treated at sustainable economic cost in the UK?	D	6	9	6 (4)	UK
24	What are the consumer and technical barriers to aquaculture using genetically modified inputs and livestock?	F	6	7	6 (5)	Global
25	What is the mechanism whereby long-chain, essential fatty acids and other micronutrients are more readily absorbed by humans through the consumption of fish, shellfish and algae products rather than neutraceutical (oil capsule) products, and how does the efficiency of uptake vary between different farmed species?	F	5	8	6 (4)	Global

tion to the overall dissimilarity among scores (Diss) to the standard deviation of the average contribution to the overall similarity (SD; Clarke 1993; Clarke and Gorley 2006).

Results

Of the 264 potential knowledge needs identified by participants and arranged into six categories, 42 were promoted through to the final scoring session (Appendices S2 and S3; Table 1), 25 top-ranked priority knowledge needs (presented in order of selection) were identified through the scores generated by participants (Table 2). Median scores for practitioners and research scientists are presented separately (Table 2). The number of those knowledge needs that can be assigned to each category within the original list ranged from 1 to 5 (Table 2). Despite consensual rephrasing of several knowledge needs, there was no re-assignment to more relevant categories. Two categories, namely 'aquaculture and the environment' and 'marine planning, management and policy' formed 40% of the list by contributing five questions each to the final 25 (Table 2). Interestingly, knowledge needs from each of the six categories are represented in the top 10 priority knowledge needs identified by practitioners (Table 2). Moreover, the supplementary knowledge need added during the plenary session and concerning 'mechanisms for knowledge exchange' was scored as the highest priority knowledge need from the process (Table 2). Significant differences occurred between the scores of the different knowledge needs (Friedman test statistic $M = 252.8$, $P < 0.001$).

The median scores obtained from practitioners and research scientists were significantly correlated for each of the prioritized 42 knowledge needs from across the themes. This indicated that the two groups scored knowledge needs with reasonable agreement (Fig. 2; $\rho = 0.53$, $P < 0.001$). In addition, an analysis of similarity revealed no significant difference in scoring patterns between

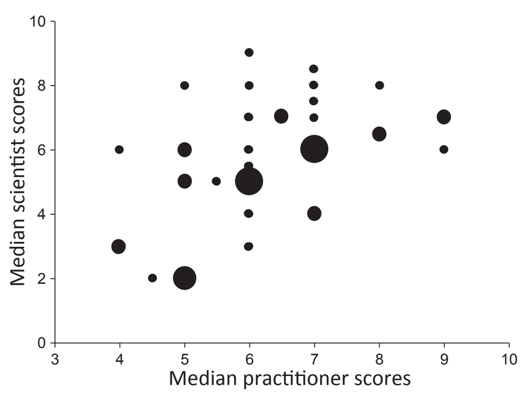

Figure 2 Median scores (1 = low priority, 10 = high priority) for each of the 42 knowledge needs given by practitioners ($n = 34$) and scientists ($n = 8$). Plots are sized according to the number of knowledge needs within each combination of scores (largest circle = 5, smallest circle = 1).

practitioners and research scientists (ANOSIM, $R = 0.05$, $P = 0.35$). The outcome of the regression for the difference in the scientist and practitioner scores for the top 25 knowledge needs gave a significant negative relationship (ANOVA, $F_{1,23} = 11.28$, $P = 0.003$). This indicated that the top-ranked knowledge needs were ranked more highly by practitioners, whereas the lower ranked priorities were ranked higher by the scientists (Fig. 3).

An ANOSIM test revealed a significant difference in the distribution of scores allocated by practitioners and research scientists within the 'husbandry methods and technology' category ($R = 0.355$, $P = 0.003$; Table 3; Fig. 4). However, no significant differences were revealed within the other five categories (Table 3). There were significant differences between scores allocated by practitioners and research scientists between the six different categories ($R = 0.11$, $P = 0.017$).

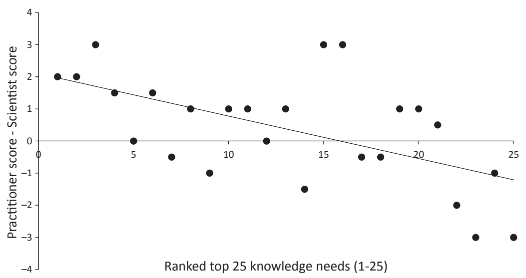

Figure 3 The difference (based on subtracting scientist scores from practitioner scores) in the median scores for each of the top 25 knowledge needs given by practitioners ($n = 34$) and scientists ($n = 8$).

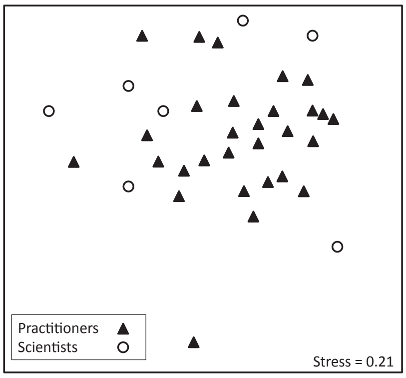

Figure 4 Non-metric multidimensional scale (MDS) ordination of scores given by practitioners (triangles) and research scientists (circles) to each of the eight potential knowledge needs to facilitate the expansion of sustainable aquaculture within the 'Husbandry methods and technology' section. Note some points may represent more than one individual.

SIMPER analysis revealed that there was a 16.9% dissimilarity in practitioner and research scientist scores within the 'husbandry methods and technology' category, with two knowledge needs contributing the most to the differences in scoring patterns: 'How can marine polychaete worms be used for the treatment of sludge from intensive aquaculture facilities and converted into a valuable secondary crop?' and 'Research into the development and optimization of economically viable aquaponics'. Practitioners scored both knowledge needs higher than scientists who scored both low. However, in both cases the scores given were low overall and therefore neither was included in the 25 priority knowledge needs list (Table 2).

Discussion

The scoring between practitioners and research scientists was consistent within and between discussion sessions, albeit for a small (but significant) difference in the 'husbandry' session, which may be attributed to a difference in the level of specialist knowledge of the scientists compared to practitioners (Table 3). Individual knowledge needs achieved sufficiently different scores that allowed

Table 3 Median practitioner (Pmed) and research scientist (Smed) scores for the six knowledge need categories and analysis of similarity (ANOSIM) output testing for significant differences* ($P < 0.05$) in scoring patterns between practitioners and research scientists within each of the knowledge need categories.

Knowledge need category	Pmed	Smed	ANOSIM output *R*	ANOSIM output *P*
Feed	6	7	−0.095	0.785
Husbandry methods and technology	5	4.5	0.355	0.003*
Aquaculture and the environment	6	6	−0.079	0.713
Marine planning, management and policy	6	6	0.005	0.437
Aquaculture supply, demand, trade and marketing	6	5.5	0.147	0.126
Disease	7	6	−0.141	0.873

them to be differentiated statistically and hence prioritized. This illustrates the robust nature of the approach to discriminate among the importance of different knowledge needs. The latter is important if the outcome is to be used as a basis for prioritizing research funding. Both practitioners and research scientists generally agreed on the content of the top 25 priority knowledge needs (that were essential to facilitate expansion of sustainable aquaculture) although there was evidence of deviation among these two groups in the ordering of these priorities. This consensus is reassuring given the wide range of stakeholders engaged throughout the process.

Of the 25 priority knowledge needs, only five were issues specifically related to the UK, whereas the remaining 20 had global application (Table 2). This is symptomatic of the global scale of seafood trade with 40% of world fish production from wild capture fisheries and aquaculture entering the international market (FAO 2009), and the fact that the UK is a net importer of seafood with imports accounting for 80% of consumption. (DEFRA 2012). UK fish trade flows are complicated: 157 k tonnes of finfish (latest available figures for 2010; CEFAS 2012) and 27 k tonnes of shellfish (2011 figures; CEFAS 2013) were produced from UK aquaculture, whereas in 2011, 376 k tonnes of fish and shellfish were landed by UK vessels into the UK, while imports and exports of fish and shellfish in 2011 were 720 and 437 k tonnes, respectively (MMO 2012). When considering UK food security, research priorities will necessarily address both current internal production issues as well as those that impact upon production overseas upon which the UK seafood industry is dependent.

The sustainable expansion of UK and global aquaculture has to be viewed in the context of limited availability of marine ingredients for feeds, with a transition to alternative feed inputs viewed as an essential requirement for all forms of aquaculture to be considered as 'aiding the ocean, not depleting it' (Naylor *et al.* 2009). However, aquaculture's dependence on forage fisheries remains hotly contested and there is growing evidence for a decoupling, with relatively stable inputs of marine ingredients supporting a steadily rising global output of fed aquaculture species (World Bank 2014). Indeed, the models used by the World Bank to project aquaculture production to 2030 assume that the importance of fishmeal and fish oil in aquaculture will decline as the industry continues to develop alternative feeds from plant-based sources and to improve efficiencies in feeding practices over time. The projected growth in fed aquaculture over the 2000–30 period, equivalent to an annual average growth rate of 3.9% per year, is much faster than the projected growth in fishmeal use in aquaculture (an average annual growth rate of 1.7%).

The frequent disconnect between science and decision-making arises from the nature of the information and knowledge produced by scientists, and information needed and used by decision-makers. A comprehensive Knowledge Management Strategy that would make relevant practitioners aware of ongoing research and any advances is currently lacking. This has resulted in a call for more communication between policymakers and scientists (Delaney and Hastie 2007; McNie 2007). When it came to the prioritization of knowledge needs in aquaculture, it was acknowledged that a significant body of research has or is addressing many of the knowledge needs identified in this process. The problem is that the research is not being converted into successful wealth-generating innovations, new businesses and societal impact (King 2004; Bonaccorsi 2007). Therefore, in recognition of the importance of knowledge management and transfer, this need was included in the final knowledge-need prioritization. Its inclusion in the final list of 42 knowledge needs was supported unanimously by both practitioners and researchers, and as the final scoring indicates, it was considered the highest priority overall.

In an attempt to address, the deficits in the current knowledge transfer practices across various interfaces: science to policy, science to industry and science to society (stakeholder engagement, outreach etc.), several initiatives have been funded under the Euro Commission 7th Framework Programme (FP7). AquaTT, an Irish-based non-profit organization, has been conducting pioneering work on Knowledge Management and Knowledge Transfer in the marine sector through its involvement in several FP7 projects such as Marine TT, STAGES, MG4U and AquaInnova. As a result of these collaborative international projects, a process for mining important and relevant information in EU-funded research projects has been developed. More work clearly needs to be carried out in order to make this information accessible to all appropriate stakeholders.

Of the remaining top 24 priority knowledge needs, the two dominant categories were 'aquaculture and the environment' and 'marine planning, management and policy'. However the highest priority knowledge needs were not from these categories, and the knowledge needs associated with environmental interactions appeared at the end of the list (19–22, Table 2). Viable alternatives to fishmeal and fish oil-based aquaculture feeds, the expansion of aquaculture and technology development associated with the expansion of aquaculture (in particular that associated with offshore aquaculture or co-location of aquaculture and marine renewable energy) and treatment of disease emerged as strong priorities.

Issues relating to feed composition and its uptake efficiency were considered priorities. Two prominent knowledge needs relate to these issues (2, 12, Table 2). The knowledge need regarding alternative dietary protein and oil sources was considered less important by scientists than practitioners. A substantial amount of research into alternative feed sources already exists. At present, fishmeal and fish oil are a cost-effective base for feeds that provide sufficient nutritional quality for high-trophic-level species. Feed and implementation of feed is the most costly part of production of farmed marine species (FAO 2006) and therefore it is not surprising that the participants consider this an important area for research. Although the share of fishmeal used by aquaculture feeds (rather than terrestrial feeds) was estimated at 3.7 million tonnes (60.8%) in 2008 (FAO 2012), representing a 20% increase since 2000 (Hall *et al.* 2011), it is predicted to decrease as viable alternatives to fishmeal and fish oil become more readily available on the market and as resource limitation drives up the price of fishmeal and fish oil (Tacon *et al.* 2006; Gatlin *et al.* 2007). Alternative feed products, such as microalgae (Durham 2010; Ju *et al.* 2012), yeast (Hatlen *et al.* 2012; Omar *et al.* 2012), bacteria (Aas *et al.* 2006), krill (Hansen *et al.* 2010; Nunes *et al.* 2011), plant-based sources (e.g. soybean, rapeseed, peas; Pratoomyot *et al.* 2010; Sookying and Davis 2011; Sørensen *et al.* 2011), as well as new innovations in technology and management, such as the use of polychaete worms (Klinger and Naylor 2012; Stabili *et al.* 2013), insects (Kroeckel *et al.* 2012; Rumpold and Schlüter 2013; PROteINSECT) and production of highly unsaturated fatty acids (HUFAs) by genetic modification (see Ruiz-Lopez *et al.* 2012 for review), need to be further investigated to reduce the cost of feed production, reliance on fishmeal and fish oil and the associated environmental impacts of use of feeds based on wild capture fisheries. These issues relate primarily to the production of high-trophic-level species that are the preferred product in western northern hemisphere countries. These species are inefficient at synthesizing HUFAs or incapable of doing so at all, whereas many freshwater and diadromous species have this ability (Sales and Glencross 2011). However, the intensification of freshwater fish production in Asia has seen an increase in fishmeal use in feeds for this sector. Given the high proportion of salmonid farming within UK aquaculture, reliant on a fishmeal-based diet (Calloway *et al.*, 2012), these knowledge needs are important in terms of UK production. At present, Chile and Norway have higher levels of fishmeal and fish oil replacement in Atlantic salmon diets than the UK industry (Tacon *et al.* 2010), which must take similar steps to move towards more sustainable feed sources. A large group of priority knowledge needs related to the spatial expansion of aquaculture in terms of the need for development in technologies, impact on resources, the environment and communities (3, 4, 6, 7, 9, 10 and 20, Table 2). Six of these knowledge needs appeared in the top 10 of the priority list and reflected the importance of adequate infrastructure to enable aquaculture to expand sustainably. Both practitioners and scientists considered these knowledge needs were important, and they were scored highly; all but one appeared within the top 10 priority knowledge needs. There are limited coastal sites where the expansion of aquaculture could occur and other users of coastal resources also compete for these spatial resources (European Commission 2012). Given the positive correlation between environmental impact and production levels (Hall *et al.* 2011), future research needs to focus on how we can best mitigate negative impacts through novel techniques. Moving aquaculture systems offshore can improve efficiency, increase the scale of a project and reduce localized environmental impacts by locating into higher energy environments (Bostock *et al.* 2010; Holmer 2010). Integration of aquaculture facilities with offshore renewable energy installations would maximize the use of the coastal zone and could reduce infrastructure and maintenance costs (Buck *et al.* 2010). There are several examples of industry-led initiatives within the UK to explore co-location of production sites with renewable energy installations. For example, the Shellfish Association of Great Britain funded the study, 'Aquaculture in Welsh Offshore Windfarms' focusing on blue mussel production on offshore wind farm sites.

Five priority knowledge needs concerned the diagnosis, prevention and treatment of pests and disease (5, 11, 13, 16 and 23, Table 2). These addressed the issues of sea lice, amoebic gill disease, norovirus and other viral contaminants in shellfish and pest management and biosecurity strategies. The most common source of mortality for farmed fish results from infectious disease (Pillay & Kutty, 2005). Given the composition of participants in the prioritization exercise, it is not surprising that two of the priority knowledge needs related to salmon farming. Given the importance of salmonid production to the UK aquaculture industry, 162 000 tonnes of salmon in 2012 (Munro and Wallace 2013), this emphasis is entirely appropriate. It was estimated that in 2006, the treatment of sea lice cost the global salmonid industry 305 million Euros (Costello 2009) and there is much concern about the resistance of lice to treatment (e.g. emamectin benzoate; Jones *et al.* 2013). Disease not only impacts production but can cause indirect market effects as a result of trade restrictions based on food safety concerns (Rodger 2001; Hansen and Onozaka 2011).

Aquaculture systems can have varying levels of impact on the environment, which offers opportunities for research that moves towards an improvement in environmental performance (Hall *et al.* 2011). Potential direct environmental impacts of aquaculture were considered priority knowledge needs but appeared in the lower part of the ranked list (Table 2). These comprised understanding the drivers that lead to harmful algal blooms (19) and a systematic review of the impact of salmon aquaculture on wild salmon populations (22). Eutrophication is evident in many freshwater aquaculture systems, although with fewer clear examples caused by marine aquaculture (Emerson 1999), and there is ongoing debate about the possible impact of fish farms on wild salmon stocks (Pearson and Black 2001; Jackson *et al.* 2013; Torrissen *et al.* 2013).

Knowledge needs that were specifically related to socioeconomics, consumer confidence and regulatory requirements were all rated higher by scientists than by practitioners. These were identification of socioeconomic and infrastructure benefits and synergies of coexistence of aquaculture and capture fisheries (17), consumer attitudes towards genetically modified inputs and livestock (24), and two knowledge needs regarding regulation and consumer confidence in the supply chain (14, 18) (Table 2). The higher rating by scientists of these knowledge needs may again emphasize the need for an effective method of knowledge exchange between scientists and practitioners.

Five of the 25 priority knowledge needs were similar to one (or in some cases two) knowledge needs identified as important questions for agriculture in an entirely separate UK food security focused exercise with different participants (Dicks *et al.* 2013). These included knowledge needs numbers 2, 8, 12, 15 and 21 (Table 2). For example, knowledge need 15 from this exercise 'What is the implication of imported vs. locally produced aquaculture products to the UK with regards to food security in producing countries and at home?' addresses a similar issue to a knowledge need prioritized in the agriculture exercise 'Assuming a substantial increase in the demand for livestock production, what systems of production, and in which locations, have the least adverse effects?' (Dicks *et al.* 2013). There were three similar knowledge needs from each exercise that focused on the use of alternative sources of protein for feed and feed efficiency. This highlights the importance of the issue of sustainable feed across the UK (and elsewhere) food production systems. Two knowledge needs (8, 21) focused on the ecosystem services provided by aquaculture, which was similar to one knowledge need from the agriculture exercise. Both knowledge needs on ecosystem services were rated higher by practitioners than scientists. However, a third knowledge need (7) concerning the environmental and associated socioeconomic effects that might occur with expansion of aquaculture in the offshore environment implicitly identifies the need to understand ecosystem services impacts and was rated higher by scientists than practitioners. These knowledge needs may reflect the widespread expectation that assessment of ecosystem services will be increasingly used in policy making (e.g. as required in the EU Biodiversity Strategy and regulatory decisions) and concurs with scientific understanding that there is a fundamental lack of knowledge of ecosystem services offshore (Beaumont *et al.* 2008; Liquete *et al.* 2013).

Next steps

In a follow-up stage to this process, the same stakeholder group would further analyse the priority knowledge needs identified. The majority of the top 25 questions or levels of information identified suggest large research programs spanning long time periods. Therefore, each knowledge need may need to be unpacked into several smaller, more focused and manageable scientific questions. In the follow-up stage, it will be important to continue to draw upon the combined knowledge of producers, processors, retailers and eNGOs, government representatives and research scientists. A continuation of collaborative work across sectors, combined with iterative discussions, will facilitate the identification of existent knowledge and knowledge gaps within the priority knowledge needs identified within this stage of the process. Moreover, it will be important to determine the economic inputs and social licensing involved in both the investigation of the priority knowledge needs and implementation of any emerging solutions (Dicks *et al.* 2012).

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Conflict of interest

With the exception of the first four and last two authors listed, all remaining authors represented the interests of organizations in this process. We do not interpret this as a conflict of interest because the process was designed to take account of a wide range of interests, including those of commercial, government and campaigning organizations (Appendix S1).

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Stakeholders involved in both stages of the overall process, their affiliations and group for the exercise [research scientist (S) or practitioner (P)].

Appendix S2. Full long list of 264 knowledge needs generated, grouped into six categories containing between 36 and 59 individual knowledge needs.

Appendix S3. Short list of 42 potential knowledge needs, promoted through to the final scoring session.